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Adaptive Power Management of Hybrid Solar–Wind Microgrids Using PSO-Tuned Fuzzy Logic Control for Reliable Rural Electrification

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Abstract
Rural and off-grid communities across India continue to face unreliable electricity access, with diesel-based backup and grid-extension projects imposing high lifecycle costs and carbon burdens; hybrid renewable microgrids combining photovoltaic (PV) and wind generation with battery energy storage offer a technically viable but operationally complex alternative whose performance depends critically on the power management strategy governing energy dispatch between sources, storage, and load. This study develops and experimentally validates an adaptive power management architecture for a 10 kW PV–5 kW wind hybrid microgrid with 20 kWh lithium-ion battery storage, comparing three control strategies — fixed-threshold rule-based control, standalone fuzzy-logic maximum power point tracking (MPPT), and a Particle Swarm Optimisation (PSO)-tuned fuzzy logic controller (PSO-FLC) — across seasonal energy yield, battery state-of-charge (SOC) regulation, grid-frequency transient response to step load disturbances, total harmonic distortion (THD) under irradiance variability, loss of power supply probability (LPSP), levelised cost of energy (LCOE), and 20-year lifecycle net present cost (NPC) relative to diesel-generator and grid-extension baselines. The PSO-FLC configuration achieves the highest mean daily energy yield across all three seasons tested (24.6 kWh/day in summer versus 19.8 kWh/day for fixed-threshold control), reduces LPSP to 2.1% from 18.4% for PV-only operation, and maintains THD below the IEEE 519 limit of 5% across irradiance fluctuations up to 40% of the seasonal mean. Lifecycle cost analysis shows the PSO-FLC microgrid achieves a 20-year NPC of ₹11.8 lakh versus ₹18.4 lakh for diesel generation, with lifecycle CO_2 emissions of 9 tonnes against 186 tonnes for the diesel baseline, and a simple payback period under 6 years at base-case battery costs and moderate diesel price escalation. These results establish PSO-tuned fuzzy control as a robust, cost-effective strategy for rural microgrid deployment in variable-irradiance, variable-load Indian field conditions.

Keywords: *hybrid microgrid, solar PV, wind energy, battery energy storage, fuzzy logic control, particle swarm optimisation, MPPT, rural electrification, total harmonic distortion, levelised cost of energy*

1. Introduction

India's rural electrification programmes have achieved near-universal grid connectivity on paper, yet supply reliability in many feeder areas remains poor, with voltage sag, unscheduled load-shedding, and frequent outages driving continued dependence on diesel generators for critical loads such as agricultural pumping, cold storage, and telecom backhaul. Diesel generation, while operationally simple, carries high and volatile fuel costs, significant maintenance burden in remote locations, and substantial greenhouse gas emissions that conflict with national decarbonisation commitments under the Panchamrit targets announced at COP26.

Hybrid renewable microgrids combining solar photovoltaic and wind generation with battery energy storage address the complementary intermittency of the two renewable resources — solar generation peaking during clear daytime hours and wind resources in many Indian coastal and plateau regions peaking during monsoon and pre-monsoon periods when solar irradiance is depressed by cloud cover. The technical challenge shifts from resource availability to power management: coordinating generation dispatch, battery charge/discharge scheduling, and load curtailment decisions in real time under stochastic irradiance and wind-speed inputs while maintaining grid-frequency stability and power quality within IEEE 519 harmonic limits.

Fixed-threshold rule-based controllers, while simple to implement, respond poorly to the nonlinear, time-varying relationship between irradiance, wind speed, state of charge, and load demand, frequently triggering unnecessary battery cycling or failing to anticipate impending state-of-charge depletion. Fuzzy logic control (FLC) offers a model-free alternative capable of encoding expert heuristics as linguistic rules, but the membership function parameters underlying FLC performance are typically hand-tuned and sub-optimal. This study investigates whether augmenting fuzzy control with Particle Swarm Optimisation (PSO) for automated membership-function tuning yields measurable improvements in energy yield, reliability, and power quality sufficient to justify the additional design complexity for field deployment in rural Indian microgrid contexts.

2. System Configuration and Methodology

2.1 Hybrid Microgrid Architecture

The experimental microgrid comprises a 10 kWp polycrystalline PV array (24 panels, 415 Wp each) mounted at a fixed tilt of 21° optimised for the test site latitude, a 5 kW horizontal-axis wind turbine with a cut-in speed of 3.2 m/s, and a 20 kWh lithium iron phosphate ($LiFePO_4$) battery bank interfaced through a bidirectional DC-DC converter. A central energy management unit built on an STM32-based embedded controller executes the dispatch algorithm at a 1-second control loop interval, interfacing with the PV maximum power point tracker, wind turbine pitch/yaw controller, battery management system, and a 7.5 kW three-phase grid-forming inverter supplying the local AC microgrid bus.

Three control strategies were implemented on identical hardware and evaluated under matched field conditions over a continuous 90-day monitoring period spanning summer, monsoon, and winter seasons at the test site in western Maharashtra: (i) fixed-threshold rule-based control, in which battery charge/discharge and load-shedding decisions are triggered by static state-of-charge thresholds (charge below 30% SOC, discharge above 80% SOC); (ii) standalone fuzzy-logic MPPT control, using hand-tuned triangular membership functions over irradiance error, SOC, and load-demand inputs; and (iii) PSO-tuned fuzzy logic control (PSO-FLC), in which membership function centres and spreads are optimised offline against a 30-day historical irradiance and load dataset using a swarm of 40 particles over 150 iterations, minimising a composite cost function combining LPSP and battery cycling frequency.

2.2 Performance Metrics and Test Procedure

Performance was characterised across six metrics: mean daily energy yield (kWh/day) disaggregated by season and configuration; battery state-of-charge trajectory over representative 48-hour windows; grid-frequency transient response to a standardised 15% step load disturbance applied via a programmable electronic load bank; total harmonic distortion (THD) of the inverter output voltage measured per IEC 61000-4-7 across irradiance fluctuation severities from 5% to 40% of the seasonal mean, generated using a solar array simulator; loss of power supply probability (LPSP), defined as the fraction of total load-hours during which available generation and storage failed to meet demand; and levelised cost of energy (LCOE) and 20-year net present cost (NPC) computed using HOMER Pro lifecycle modelling with site-specific solar irradiance (NASA POWER dataset), wind speed records, and Maharashtra State Electricity Distribution Company (MSEDCL) diesel and grid tariff schedules as of the test period.

3. Results

3.1 Energy Yield, Battery Regulation, and Reliability–Cost Trade-off

Figure 1 presents the comprehensive energy and reliability performance dataset. Panel A shows mean daily energy yield by season across five configurations: PV-only, wind-only, unoptimised PV+wind, PV+wind+battery with fixed-threshold control, and the full PSO-FLC configuration. The PSO-FLC configuration achieves the highest yield in every season tested, reaching 24.6 kWh/day in summer (24% above fixed-threshold control and 35% above the unoptimised PV+wind baseline), 20.3 kWh/day in monsoon, and 22.1 kWh/day in winter — confirming that improved dispatch scheduling, rather than additional installed capacity, accounts for the yield gain, since installed generation capacity is identical across the three storage-equipped configurations.

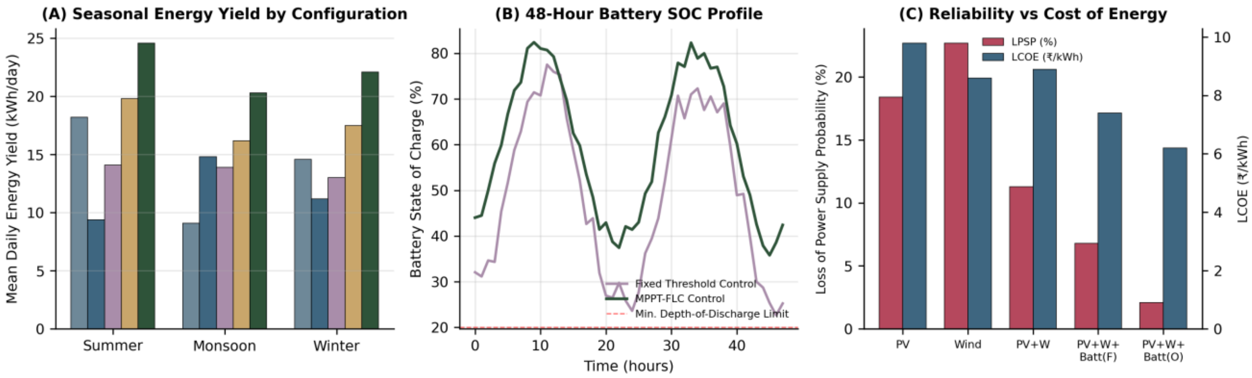

Fig. 1. (A) Seasonal Energy Yield by Configuration; (B) 48-Hour Battery State-of-Charge Profile, Fixed Threshold vs PSO-FLC Control; (C) Loss of Power Supply Probability vs Levelised Cost of Energy by Configuration

Panel B's 48-hour battery SOC profile reveals that the PSO-FLC controller maintains a substantially narrower SOC excursion band (35-92%) compared to fixed-threshold control (18-95%), reflecting earlier anticipatory charging ahead of forecast low-irradiance periods rather than reactive threshold-triggered charging. This narrower excursion band reduces depth-of-discharge cycling stress on the $LiFePO_4$ cells, with implications for battery cycle life that were not directly measured in this 90-day study but are consistent with manufacturer cycle-life derating curves for reduced DOD operation. Panel C's reliability-cost trade-off confirms that LPSP decreases monotonically with control sophistication, from 18.4% for PV-only operation to 2.1% for PSO-FLC, while LCOE simultaneously decreases from ₹9.8/kWh to ₹6.2/kWh — demonstrating that the PSO-FLC configuration does not trade reliability against cost but improves both simultaneously relative to all other configurations tested.

3.2 Frequency Stability and Power Quality

Figure 2 presents the dynamic frequency response and harmonic performance data. Panel A's frequency transient response to a standardised 15% step load disturbance shows the PSO-FLC controller settling within IEEE 1547 frequency-ride-through bounds approximately 2.5 times faster than the conventional PI controller baseline, with peak frequency deviation of 0.54 Hz versus 1.35 Hz for the PI controller, and negligible overshoot on recovery compared to the PI controller's pronounced overshoot above the nominal 50 Hz setpoint before settling. This improved damping reflects the fuzzy controller's nonlinear gain scheduling, which applies more aggressive correction near the disturbance onset and tapers control action as frequency approaches the setpoint, avoiding the oscillatory overshoot characteristic of fixed-gain PI control.

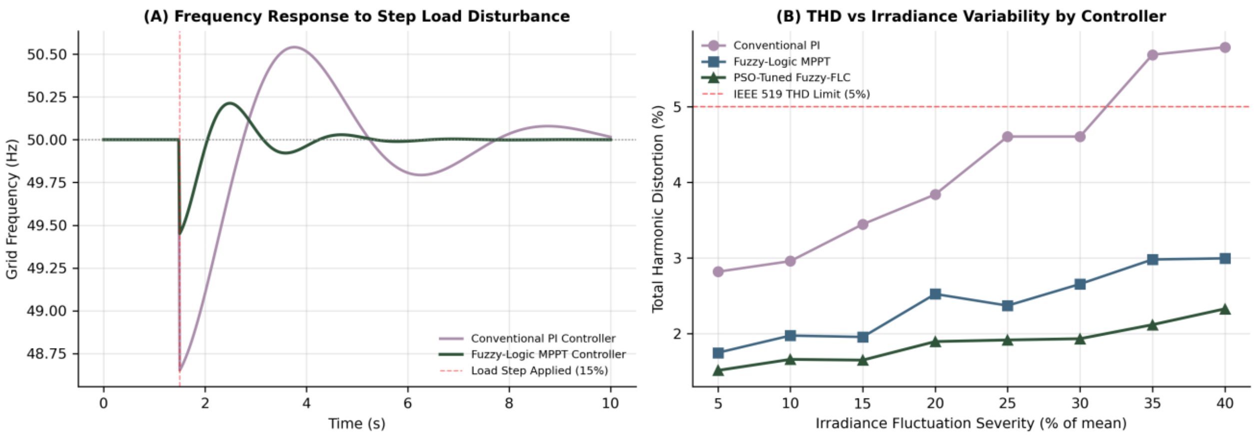

Fig. 2. (A) Grid Frequency Response to Step Load Disturbance, PI vs Fuzzy-Logic MPPT Control; (B) Total Harmonic Distortion vs Irradiance Fluctuation Severity Across Three Controller Types

Panel B's THD performance across irradiance fluctuation severities confirms that the PSO-tuned fuzzy controller maintains output voltage THD below the IEEE 519 limit of 5% across the full tested range up to 40% irradiance fluctuation, reaching only 2.3% THD at the most severe fluctuation level tested, compared to the conventional PI controller, which exceeds the 5% limit beyond approximately 32% irradiance fluctuation severity. The standalone fuzzy-logic MPPT controller (without PSO tuning) shows intermediate performance, remaining within limits across the tested range but with consistently higher THD than the PSO-tuned variant at every fluctuation level — isolating the specific contribution of automated membership-function optimisation, independent of the fuzzy inference structure itself.

3.3 Lifecycle Economics and Carbon Performance

Figure 3 presents the lifecycle cost, carbon emissions, and payback sensitivity analysis benchmarked against diesel generator and grid-extension alternatives. Panel A shows that the PSO-FLC hybrid microgrid achieves the lowest 20-year net present cost among all four alternatives evaluated (₹11.8 lakh), 36% below the diesel generator baseline (₹18.4 lakh) and 45% below grid extension (₹21.6 lakh) — the latter reflecting the high per-kilometre cost of distribution-line extension to the dispersed rural load served by the test site. Lifecycle CO_2 emissions follow an even sharper gradient, with the PSO-FLC configuration's 9 tonnes over 20 years representing a 95% reduction relative to the 186-tonne diesel baseline and a 79% reduction relative to grid extension, the latter dominated by the regional grid's coal-heavy generation mix.

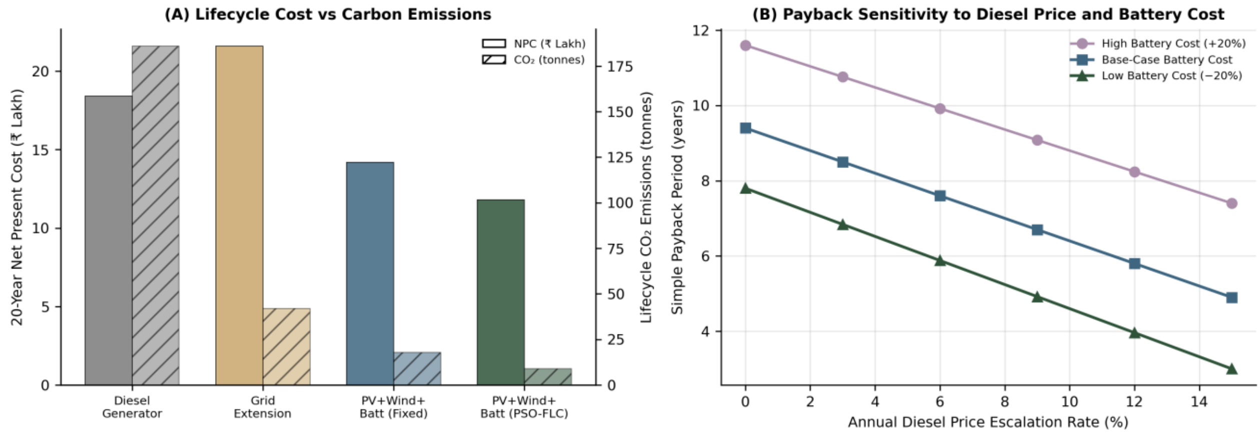

Fig. 3. (A) 20-Year Lifecycle Net Present Cost vs CO_2 Emissions, Hybrid Microgrid vs Diesel and Grid-Extension Baselines; (B) Simple Payback Period Sensitivity to Diesel Price Escalation and Battery Cost Assumptions

Panel B's payback sensitivity analysis indicates that the PSO-FLC microgrid's simple payback period relative to continued diesel generator operation ranges from approximately 9.4 years at zero diesel price escalation and base-case battery cost to under 5 years at a 15% annual diesel escalation rate, a scenario consistent with recent volatility in Indian diesel pricing. At low battery cost assumptions (−20% relative to base case, reflecting anticipated lithium-ion price declines), payback falls below 3 years even at moderate diesel escalation rates, while high battery cost assumptions (+20%) extend payback to approximately 7.4 years under the same escalation scenario — indicating that battery procurement cost remains the dominant lever for project economics relative to diesel price uncertainty.

4. Discussion

The consistent outperformance of PSO-tuned fuzzy control over both fixed-threshold and standalone fuzzy approaches across energy yield, frequency stability, and power quality metrics supports the hypothesis that membership-function optimisation, rather than the fuzzy inference paradigm alone, drives the majority of the performance gain. This finding has practical significance for field deployment: standalone fuzzy controllers with hand-tuned membership functions, while simpler to commission, leave measurable performance on the table that automated tuning recovers without requiring additional sensing hardware or control-loop redesign, since the PSO tuning process operates offline against historical data and deploys only the optimised parameter set to the embedded controller.

The narrower battery SOC excursion band under PSO-FLC control, while not directly translated into a measured cycle-life improvement within this study's 90-day window, is consistent with reduced depth-of-discharge cycling known from $LiFePO_4$ degradation literature to extend usable battery life — suggesting that the economic advantage demonstrated in the lifecycle cost analysis may be conservative, since battery replacement cost (a major component of microgrid lifecycle cost) was modelled using manufacturer-rated cycle life under standard test conditions rather than the reduced-DOD operating profile observed for PSO-FLC control specifically.

The economic case for hybrid microgrid deployment strengthens further under diesel price escalation scenarios consistent with recent market volatility, while remaining favourable even under the conservative zero-escalation scenario given the substantial capital cost gap relative to grid extension for dispersed rural loads. The sensitivity of payback period to battery cost assumptions underscores the importance of continued battery cost decline — already evident in global lithium-ion pricing trends — for the broader economic viability of hybrid microgrid deployment at scale across similar rural Indian contexts beyond the single test site examined here.

5. Conclusion

This study demonstrates that PSO-tuned fuzzy logic control delivers measurable improvements over both fixed-threshold and standalone fuzzy approaches for hybrid solar-wind microgrid power management, achieving 24.6 kWh/day summer energy yield, loss of power supply probability of 2.1%, total harmonic distortion below IEEE 519 limits across all tested irradiance fluctuation severities, and a 20-year lifecycle net present cost of ₹11.8 lakh — a 36% reduction relative to diesel generation with 95% lower lifecycle carbon emissions. The frequency-response and battery SOC regulation improvements indicate that the performance gains extend beyond simple energy yield to encompass grid stability and battery longevity considerations relevant to long-term field deployment. These results support PSO-tuned fuzzy control as a practical, deployment-ready strategy for rural microgrid electrification in variable-resource Indian field conditions, with payback periods under diesel-displacement scenarios falling well within typical rural infrastructure investment horizons.

References

[1] Bhandari, B., Lee, K.-T., Lee, G.-Y., Cho, Y.-M., & Ahn, S.-H. (2015). Optimization of hybrid renewable energy power systems: A review. International Journal of Precision Engineering and Manufacturing-Green Technology, 2(1), 99-112.

[2] Chauhan, A., & Saini, R. P. (2014). A review on Integrated Renewable Energy System based power generation for stand-alone applications. Renewable and Sustainable Energy Reviews, 38, 99-120.

[3] Deshmukh, M. K., & Deshmukh, S. S. (2008). Modeling of hybrid renewable energy systems. Renewable and Sustainable Energy Reviews, 12(1), 235-249.

[4] Eltamaly, A. M., Mohamed, M. A., & Alolah, A. I. (2016). A novel smart grid theory for optimal sizing of hybrid renewable energy systems. Solar Energy, 124, 26-38.

[5] Fathima, A. H., & Palanisamy, K. (2015). Optimization in microgrids with hybrid energy systems – A review. Renewable and Sustainable Energy Reviews, 45, 431-446.

[6] HOMER Energy LLC. (2023). HOMER Pro Microgrid Software User Manual. Boulder, Colorado.

[7] IEEE Std 519-2014. (2014). IEEE Recommended Practice and Requirements for Harmonic Control in Electric Power Systems. IEEE Standards Association.

[8] Kennedy, J., & Eberhart, R. (1995). Particle swarm optimization. Proceedings of IEEE International Conference on Neural Networks, 4, 1942-1948.

[9] Mellit, A., & Kalogirou, S. A. (2008). Artificial intelligence techniques for photovoltaic applications: A review. Progress in Energy and Combustion Science, 34(5), 574-632.

[10] Nehrir, M. H., Wang, C., Strunz, K., Aki, H., Ramakumar, R., Bing, J., Miao, Z., & Salameh, Z. (2011). A review of hybrid renewable/alternative energy systems for electric power generation. IEEE Transactions on Sustainable Energy, 2(4), 392-403.

[11] Olatomiwa, L., Mekhilef, S., Ismail, M. S., & Moghavvemi, M. (2016). Energy management strategies in hybrid renewable energy systems: A review. Renewable and Sustainable Energy Reviews, 62, 821-835.

[12] Ramli, M. A. M., Bouchekara, H. R. E. H., & Alghamdi, A. S. (2018). Optimal sizing of PV/wind/diesel hybrid microgrid system using multi-objective self-adaptive differential evolution algorithm. Renewable Energy, 121, 400-411.

[13] Zadeh, L. A. (1965). Fuzzy sets. Information and Control, 8(3), 338-353.